AD-A066 890 NAVY ELECTRONICS LAB SAN DIEGO CALIF F/G 20/1
LONG-RANGE SHALLOW-WATER BOTTOM REVERBERATION,(U)
1960 K V MACKENZIE

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(6) LONG-RANGE SHALLOW-WATER BOTTOM REVERBERATION

(10) K. V. Mackenzie
U. S. Navy Electronics Laboratory
San Diego 52, California

(11) 1960

(12) 26p.

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ABSTRACT

A theory is presented which enables the computation to be made of 200- to 5000-cps bottom reverberation returning from very great ranges in shallow-water. Typical computed curves are presented for reverberation level vs range/water-depth. Computed curves are presented for scattering strength vs range/water-depth. These later curves are presented for both the isospeed and negative sound-speed gradient cases.

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INTRODUCTION

The problem of the prediction of long-range active detection possibilities in shallow water involves the estimate of the two-way transmission losses and the estimates of the reverberation conditions which include an assessment of the roles of surface, volume, and bottom reverberation. The theory developed, for long-range bottom reverberations in shallow-water, follows almost as a corollary from a previous paper[1] on long-range shallow-water transmission losses that was based on ray methods. The volume, surface, and bottom reverberations from long ranges in shallow-water are inseparable. However, in some unpublished work by the author, it was found that the 700-cps reverberation returning from a range of 11,000 yards in 28-fathom water, when the wind was blowing 30 knots and the sea was state 5, yielded a reverberation strength of only -58 db per square yard. This could be entirely attributed to the bottom. The behavior of surface and volume reverberation at the lower frequencies is unavailable. Only bottom reverberation will be discussed because it is likely the only important reverberation for the fre-

quencies of interest for this paper which are from 200- to 5000-cps. Bottom reverberation for a given bottom was found to exhibit no marked frequency dependence.[2,3,4] Any surface reverberation could be treated as additional bottom reverberation. The treatment of any volume reverberation is straightforward with the transmission losses previously computed.[1]

THEORY

Reverberation Behavior

The two common assumptions[3] for the behavior of the bottom scattered sound are illustrated in Fig. 1. The solid circle tangent to the bottom area illustrates Lambert's cosine law for diffuse reflection. Lambert's law states that the intensity, I_r, at a unit distance from the unit area, of the energy scattered at any angle, θ (not necessarily in the plane of incidence), is $\mu_2 \sin\theta$ times the incident intensity, where μ_2 is a constant peculiar to the diffusing surface. This gives

$$I_r = \mu_2 I_i \sin\theta = \mu_2 I_\phi \sin\phi \sin\theta \qquad (1)$$

The dashed semi-circle in Fig. 1 illustrates the alternate assumption

which is that the sound is scattered uniformly in all directions. In this case the value for intensity, I_r, at a unit distance from the unit area

$$I_r = \mu_1 I_i = \mu_1 I_\phi \sin\phi \tag{2}$$

where μ_1 is a constant.* The relative magnitudes in Fig. 1 have no significance but were arbitrarily picked for clarity of illustration. Both of these mechanisms implicitly assume no azimuth dependence.

For many applications the interest has been confined to the case where $\theta = \phi$ and Lambert's reverberation has been referred to as a sine-squared dependence and omnidirectional reverberation as a sine dependence. This is because the incident intensity I_i, varies as $\sin\phi$. Equations (1) and (2) are generalized for convenience by

$$I_r = \mu_K I_\phi \sin^{K-1}\theta \sin\phi \tag{3}$$

where $K = 1$ corresponds to omnidirectional scattering and $K = 2$ corresponds to Lambert's law. There is no limitation that $\theta = \phi$. Some 24-kcps experimental data[3] favor $K = 1$ and some favor $K = 2$. The 55-kcps data presented

- -

*Many authors have used a factor 2π with this assumption together with a scattering coefficient m_b, where $m_b/2\pi = \mu_1$.

by Urick[4] for sand and rock bottoms (areas A and B) follow the sine-squared dependence very closely from his smallest grazing angle of 10° to normal incidence. Figure 2 presents some data that were furnished to the author by ~~Dr. H. L. Saxton~~ R.M. Patterson in a personal communication. The value of $K = 1$ is obviously the best for this particular rough bottom.

__Transmission Losses__

The ray method that was used in the previous paper[1] with the assumption of random phase will be used in this paper. The scattered sound is considered as a new source. Considering the scattered sound from a unit area, Lambert's law, Eq. (1) gives a vertical directivity, as shown in Fig. 1 by the solid tangent circle, of $\sin \theta$; and, the assumption of uniform scattering, Eq. (2), gives an omnidirectional pattern shown by the dashed circle. These new vertical directivities are independent of the source depth to wavelength ratio, d/λ, and ϕ and can be used in exactly the same manner as the $4 \sin^2 (\frac{2\pi d}{\lambda} \sin \phi)$ was used in determining the transmission loss from the source to the scattering area.[1] In this case, ~~of~~ the expression for the returning intensity at the receiver becomes

$$I_B = \frac{\mu_s A I_o}{RD} \int_0^{\frac{\pi}{2}} \sin^{K-1} \theta \; r^{\frac{R \tan \theta}{2D}} \cos \theta \, d\theta \qquad (4)$$

where I_B is the horizontal intensity back at the receiver.

R = Range

D = Water depth

A = effective insonified area

r = ratio of reflected intensity to incident intensity at grazing angle ϕ.

The reflection of coefficient, r, is a function of the ratio of the sound speed, c_2, in the bottom to the sound speed, c_1, in the water; the ratio of the density, ρ_2 of the bottom to the density, ρ_1, of the water; the volume attenuation of the bottom, α/β, in nepers per radian; and the grazing angle.[1]

The anomaly, A_R, the departure from simple spherical spreading for zero seawater attenuation is

$$A_R = 10 \log_{10} \frac{D}{R} - 10 \log_{10} \int_0^{\frac{\pi}{2}} \sin^{K-1}\theta \; r^{\frac{R \tan \theta}{2D}} \cos \theta \, d\theta \qquad (5)$$

The one-way transmission loss for the reverberation returning from range R to the receiver is

$$H_R = 20 \log_{10} R + A_R + 3.3 \times 10^{-3} f^{3/2} R \qquad (6)$$

where the last term accounts for the volume attenuation in the sea water[5] and f is in kcps and R is in yards. The anomalies for some typical conditions are shown on Fig. 3 for $K = 1$ and $K = 2$. The curves for $K = 1$ are just 3-db lower than the omnidirectional curves of the transmission loss paper[1] because a surface image is not considered for the reverberation mechanism.

<u>Incident Intensity</u>

The incident intensity at the bottom can be obtained from the horizontal intensity previously developed[1] by leaving $\cos \phi$ out of the expression. The incident intensity for the isospeed condition is then

$$dI_\phi = \frac{4I_o}{RD} \sin^2 \left(\frac{2\pi d}{\lambda} \sin \phi \right) r^{\frac{R \tan \phi}{2D}} \, d\phi \qquad (7)$$

where dI_ϕ = incident intensity at a grazing angle ϕ on the scattering area

I_o = free-field intensity of a simple source at one yard.

The incident intensity dI_1 on a <u>unit</u> area of the bottom at an angle ϕ is

$$dI_1 = dI_\phi \sin \phi \qquad (8)$$

Integrating from 0 to $\pi/2$, gives the total incident intensity, I_1, as

$$I_1 = \frac{4I_o}{RD} \int_0^{\frac{\pi}{2}} \sin^2 \left(\frac{2\pi d}{\lambda} \sin \phi \right) r^{\frac{R \tan \phi}{2D}} \sin \phi \, d\phi \qquad (9)$$

Reverberation Level

The term reverberation level, RL, is defined as the reverberation back at the receiver due to a nearby source ~~with a level~~ producing a sound pressure of 1 μb at 1 yard. Combining Eqs. (4) and (9) gives

$$RL = 10 \log_{10} \left[\frac{4\mu_K A}{\pi^2 R D} \int_0^{\frac{\pi}{2}} \sin^2\left(\frac{2\pi d}{\lambda} \sin\phi\right) r^{\frac{R \tan\phi}{2D}} \sin\phi \, d\phi \int_0^{\frac{\pi}{2}} \sin^{K-1}\theta \, r^{\frac{R\tan\theta}{2D}} \cos\theta \, d\theta \right] \qquad (10)$$

If the receiver is by the source, the effective insonified area, A, at any instant is $A = \psi R c_1 \tau / 2$

where ψ is the horizontal beam width, and τ is the transmitted pulse duration. It is convenient to keep the units of R and D in yards and c in yards per second. Typical normalized average Reverberation Level vs Range/Depth curves are presented in Figs. 4, 5, and 6 for a horizontal beam-width of 10°, a sound-speed of 1600 yards/second, a pulse duration of 0.1 second, and a value for $\mu_K = 10^{-3}$.

REVERBERATION STRENGTH

The quantity reverberation strength, RS, is defined here as

$$RS = 10 \log_{10} \frac{I_K}{I_\phi} A \qquad (11)$$

where A is the effective area from which the reverberation is coming at any given instant. This is analogous to a ship's target strength, TS. Scattering strength per unit area, S, may be defined[4] as

$$S = 10 \log_{10}\left(\frac{\frac{I}{A}}{I_\phi}\right) \qquad (12)$$

Reverberation strength is a more useful concept than reverberation level because the reverberation strength can be compared directly to the target strength of a ship. Reverberation strength is also convenient for bistatic computations when the receiver is not by the source.

Isospeed Conditions

There will be some effective angle of incidence, ϕ_e, at which all of the sound may be considered to impinge on the bottom. This is determined by

$$\sin \phi_e = \left\langle \sin \phi \right\rangle = \frac{\int_0^{\frac{\pi}{2}} \sin^2\left(\frac{2\pi d}{\lambda} \sin \phi\right) r^{\frac{R \tan \phi}{2D}} \sin \phi \, d\phi}{\int_0^{\frac{\pi}{2}} \sin^2\left(\frac{2\pi d}{\lambda} \sin \phi\right) r^{\frac{R \tan \phi}{2D}} \, d\phi} \qquad (13)$$

Some typical effective incident angles, ϕ_e, are shown on Fig. 7.

¶ It is convenient to define an effective angle of reverberation θ_e from which all of the reverberation may be considered to come - or better yet, the value

may be considered to be that of an equivalent omnidirectional source.

$$\sin \theta_e \frac{\int_0^{\pi/2} \sin^{K-1}\theta \; r^{\frac{R \tan \theta}{2D}} \cos\theta \, d\theta}{\int_0^{\pi/2} r^{\frac{R \tan \theta}{2D}} \cos\theta \, d\theta} \qquad (14)$$

Equation (14) is unity for K = 1. For K = 2, Eq. (14) yields effective angles of reverberation, θ_e, which have about the same value as the corresponding ϕ_e and decrease with range in the same manner.

Normalized reverberation strength vs. range/depth curves are given in Figs. 8, 9, and 10 for some typical bottoms to illustrate the effects of the several parameters. The feature is the much smaller range of levels than that exhibited by Figs. 4, 5, and 6. The reverberation level can be obtained by subtracting the sum of the transmission loss to the reverberating area and the transmission loss from the reverberating area from the reverberation strength. Note that the omnidirectional loss back is used for both K = 1 and K = 2 because sin θ_e was determined with Eq. (14).

Downward Refraction

Downward refraction will increase the grazing angle and shift ϕ_e to

somewhat larger angles. Some calculations were made for the sound-speed vs depth profiles shown in Fig. 11. These calculations were made for a water depth of 50 yards. The dependence on the dimensionless parameter range/depth is not exact; but, because it is a fair approximation, the reverberation strengths are presented normalized in Fig. 12. The curves for N=2 for areas I and III are not exact but are based on the fair approximation, for these conditions, that $\langle \sin^2\phi \rangle = \sin\phi_e \sin\theta_e$. The corresponding isospeed curve for N=2 was obtained by interpolation between the available UNIVAC computations for $c_2/c_1 = 1.02$ and 1.04. All the computed values of reverberation strength - which is comparable to target strength - fall in approximately the same range of values. The corresponding transmission losses differ considerably. In fact, the calculations for area I on Fig. 12 are stopped where the transmission loss became exceedingly large and the computing machine ran out of digits.

SUMMARY

The preceding equations establish a method for computing bottom reverberation in terms of the physical properties of the bottom. Urick[6] found no azimuth dependence and this of course is implicit in Eqs. (1) and (2). The level of the reverberation, LR, at a receiver at an arbitrary location can be determined from the source level L_1 in db re μb at 1 yard, the

reverberation strength RS, the transmission loss H_T from the source to the reverberating area, and the transmission loss H_R from the reverberating area to the receiver. The effective area to compute RS at any instant t due to a pulse length τ will be determined by the geometry of the intersecting source and receiver beams. The choice of K and the value for the coefficient, μ, will have to be determined from the best available information on the particular bottom. The level of the reverberation is

$$LR = L_1 + RS - H_T - H_R \tag{15}$$

The transmission loss H_T to the reverberating area is

$$H_T = 20 \log_{10} R_T + A_T + 3.3 \times 10^{-5} f^{3/2} R_T \tag{16}$$

where A_T is given in the transmission loss paper.[1] (The incident intensity computed from Eq. (7) is not strictly the same as the horizontal intensity because the cos ϕ has been omitted. However, the angles are small and the difference is only a small fraction of a db for $R/_D$ 10.)

Accurate close-range reverberation studies over different bottoms and especially with lower frequencies are needed for grazing angles from 1° to 10°.

Reverberation strength is more significant than reverberation level. The transmission losses should *always* be determined when any reverberation data are obtained in order that the more fundamental reverberation strengths can be calculated.

ACKNOWLEDGMENTS

The author wishes to thank the David Taylor Model Basin where Eqs. (10), (13), and (14) were computed on the UNIVAC for a large number of conditions in 1959. The author also wishes to thank Mr. S. V. Porter and Mrs. G. B. Porter, who made the downward refraction calculations on the IBM 604 computer at NRL and Mrs. M. R. Miller who plotted many of the curves.

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2. K. V. Mackenzie, "Bottom Reverberation at 530 - 1030 cps in 2100-Fathom Water, JASA (in press).

3. National Defense Research Committee, Division 6, "Physics of Sound in the Sea", Summary Technical Report, Vol. 8, Chapter 15 (1946)/

4. R. J. Urick, JASA, 26, 231 (1954).

5. M. J. Sheehy and R. Halley, JASA, 29, 262, (1957).

6. R. J. Urick, JASA, 32, 351, (1960).

ILLUSTRATIONS

Figure 10 - Normalized reverberation strength vs range/depth for a bottom with $c_2 = 0.99c_1$ and $\rho_2 = 1.30\rho_1$.

Figure 11 - Profiles of sound-speed vs depth for areas I and III that were used for the computations.

Figure 12 - Generalized reverberation strength vs range/depth curves for an isospeed condition and for the profiles of areas I and III.

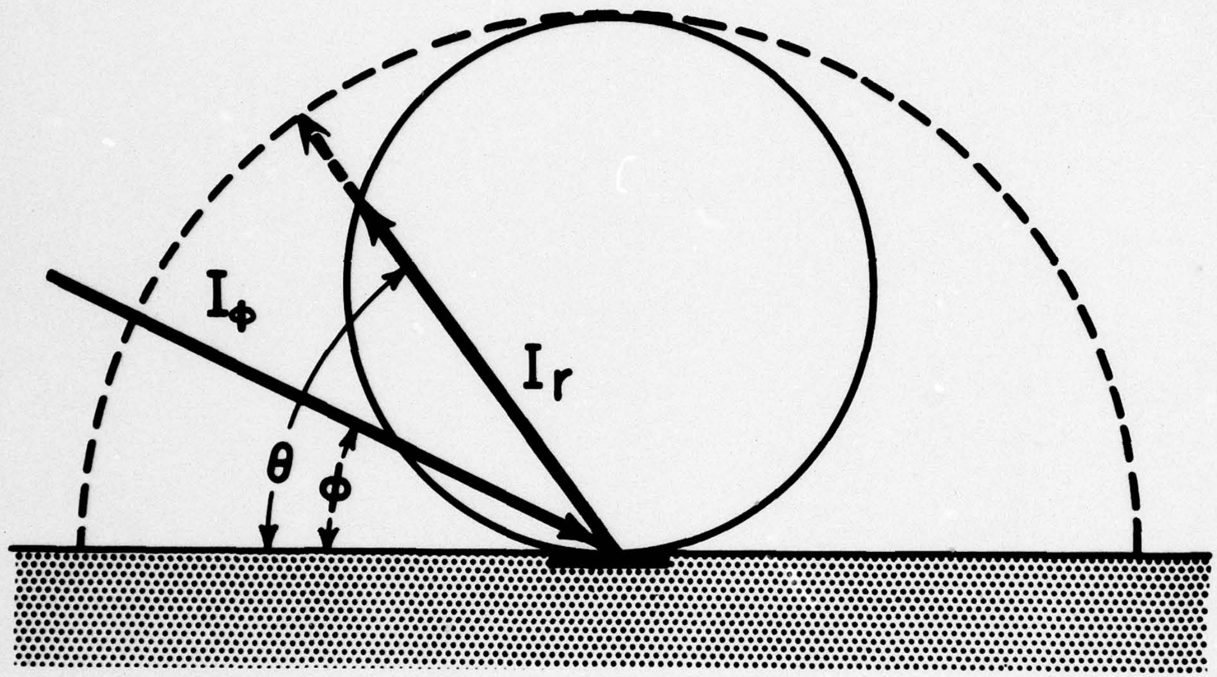


FIG. 1

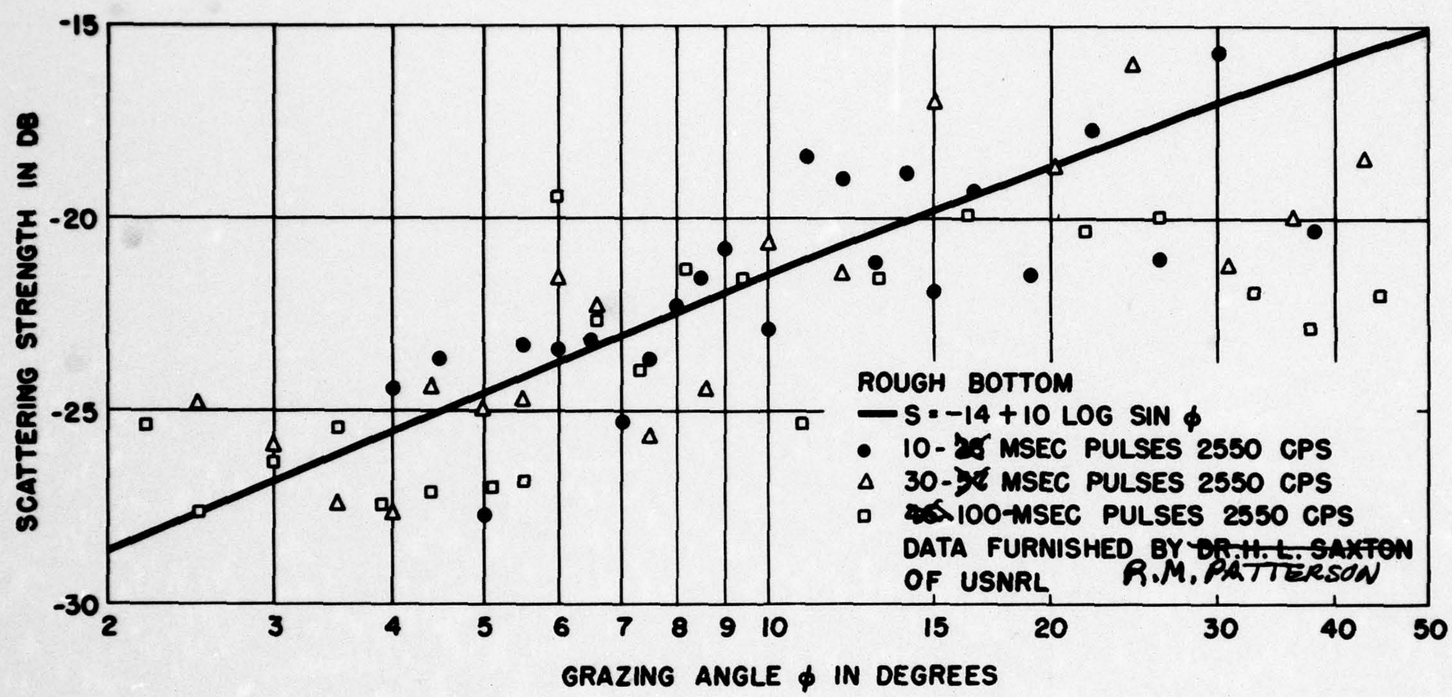
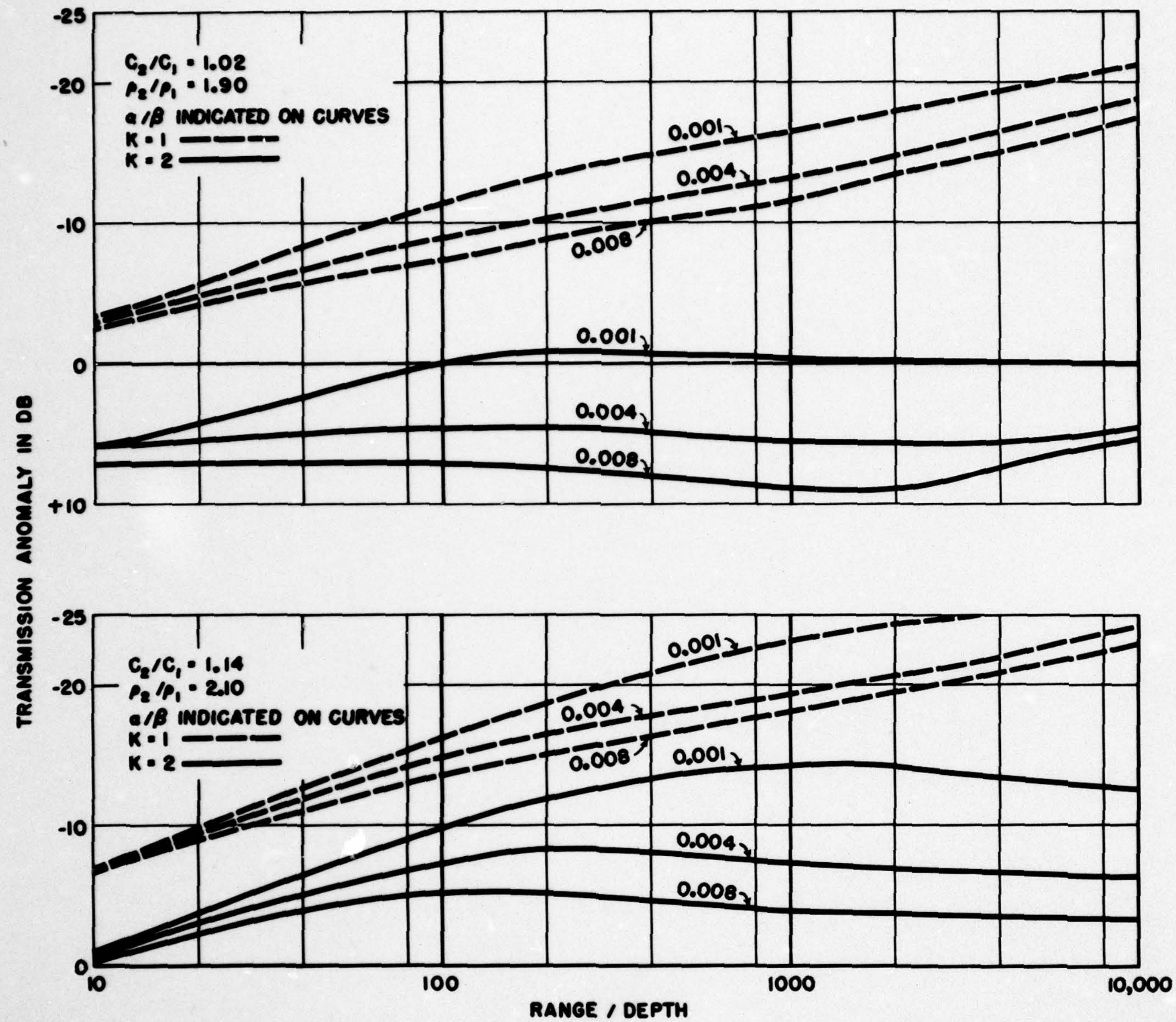

SCATTERING STRENGTH IN DB
-15
-20
-25
-30
2
3
4
5
6
7
8
9
10
15
20
30
40
50
GRAZING ANGLE ϕ IN DEGREES
ROUGH BOTTOM
S = -14 + 10 LOG SIN ϕ
10-~~25~~ MSEC PULSES 2550 CPS
30-~~75~~ MSEC PULSES 2550 CPS
~~45~~ 100 MSEC PULSES 2550 CPS
DATA FURNISHED BY ~~DR. H. L. SAXTON~~ R.M. PATTERSON
OF USNRL

FIG. 2



$C_2/C_1 = 1.02$
$\rho_2/\rho_1 = 1.90$
α/β INDICATED ON CURVES
K = 1
K = 2
0.001
0.004
0.008
0.001
0.004
0.008
-25
-20
-10
0
+10
$C_2/C_1 = 1.14$
$\rho_2/\rho_1 = 2.10$
α/β INDICATED ON CURVES
K = 1
K = 2
0.001
0.004
0.008
0.001
0.004
0.008
-25
-20
-10
0
10
100
1000
10,000
TRANSMISSION ANOMALY IN DB
RANGE / DEPTH

FIG. 3

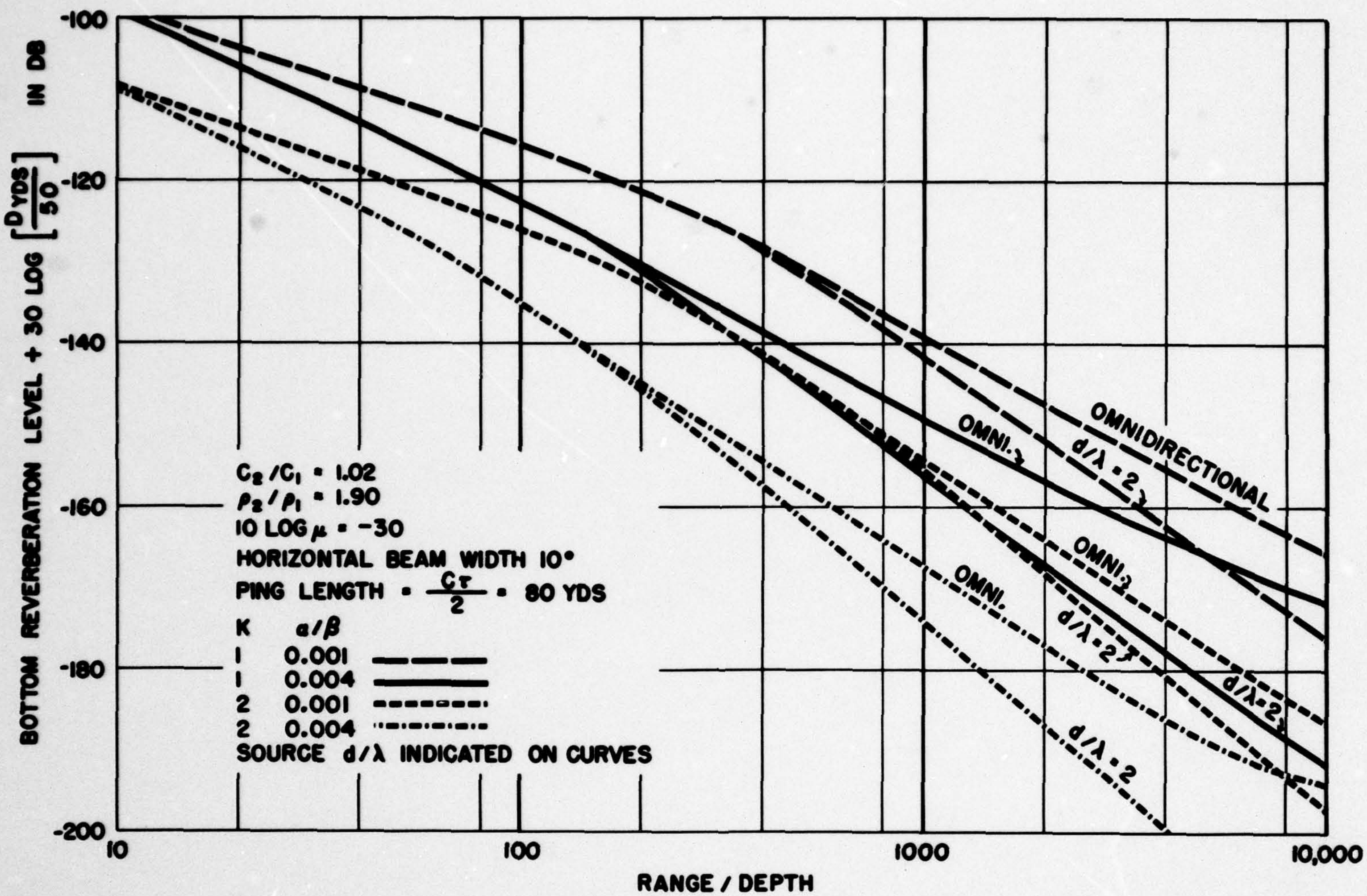

BOTTOM REVERBERATION LEVEL + 30 LOG $\left[\frac{D_{YDS}}{50}\right]$ IN DB
-100
-120
-140
-160
-180
-200
10
100
1000
10,000
RANGE / DEPTH
OMNIDIRECTIONAL
$d/\lambda = 2$
OMNI.
OMNI.
OMNI.
$d/\lambda = 2$
$d/\lambda = 2$
$d/\lambda = 2$
$C_2/C_1 = 1.02$
$\rho_2/\rho_1 = 1.90$
$10 \log \mu = -30$
HORIZONTAL BEAM WIDTH 10°
PING LENGTH = $\frac{C\tau}{2}$ = 80 YDS
K α/β
1 0.001
1 0.004
2 0.001
2 0.004
SOURCE d/λ INDICATED ON CURVES

FIG. 4

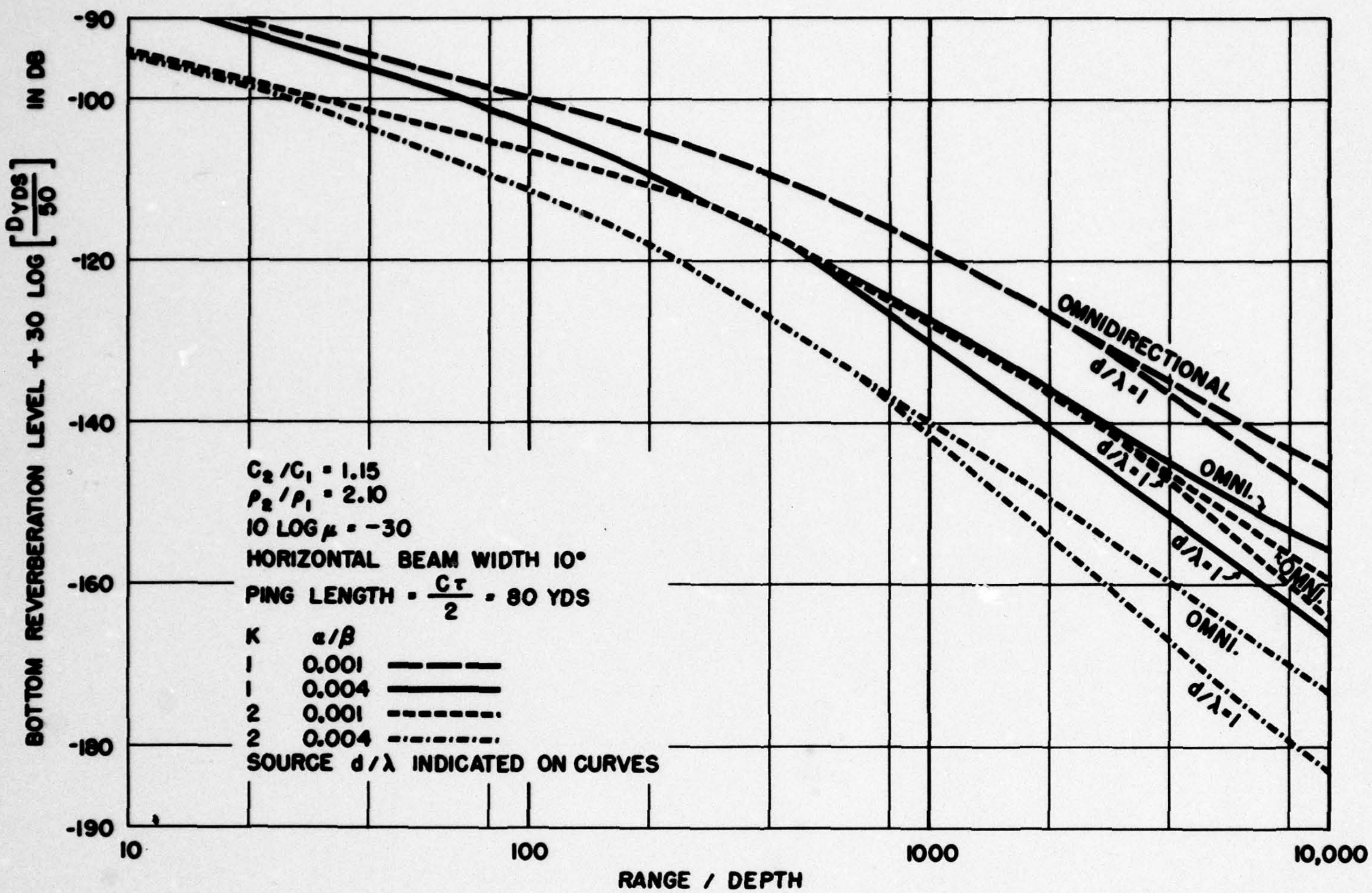
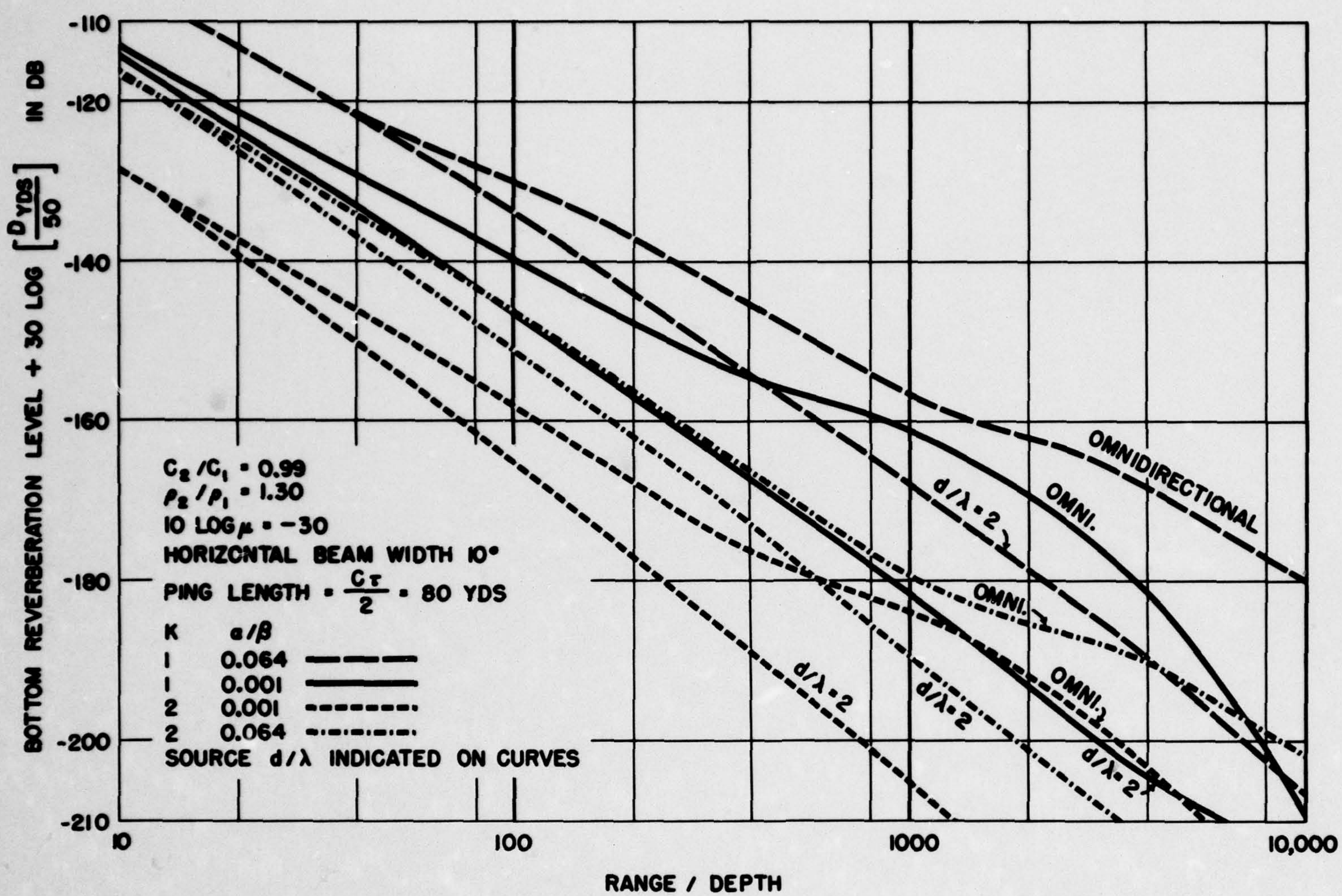

BOTTOM REVERBERATION LEVEL + 30 LOG [D YDS / 50] IN DB
-90
-100
-120
-140
-160
-180
-190
10
100
1000
10,000
RANGE / DEPTH
OMNIDIRECTIONAL
d/λ=1
OMNI.
d/λ=1
OMNI.
d/λ=1
OMNI.
d/λ=1
C2/C1 = 1.15
ρ2/ρ1 = 2.10
10 LOG μ = -30
HORIZONTAL BEAM WIDTH 10°
PING LENGTH = Cτ/2 = 80 YDS
K α/β
1 0.001
1 0.004
2 0.001
2 0.004
SOURCE d/λ INDICATED ON CURVES

FIG.5



-110
-120
-140
-160
-180
-200
-210
BOTTOM REVERBERATION LEVEL + 30 LOG $\left[\frac{D_{YDS}}{50}\right]$ IN DB
10
100
1000
10,000
RANGE / DEPTH
OMNIDIRECTIONAL
OMNI.
$d/\lambda = 2$
OMNI.
OMNI.
$d/\lambda = 2$
$d/\lambda = 2$
$d/\lambda = 2$
$C_2/C_1 = 0.99$
$\rho_2/\rho_1 = 1.30$
$10 \log \mu = -30$
HORIZONTAL BEAM WIDTH 10°
PING LENGTH = $\frac{C\tau}{2}$ = 80 YDS
K a/β
1 0.064
1 0.001
2 0.001
2 0.064
SOURCE d/λ INDICATED ON CURVES

FIG. 6

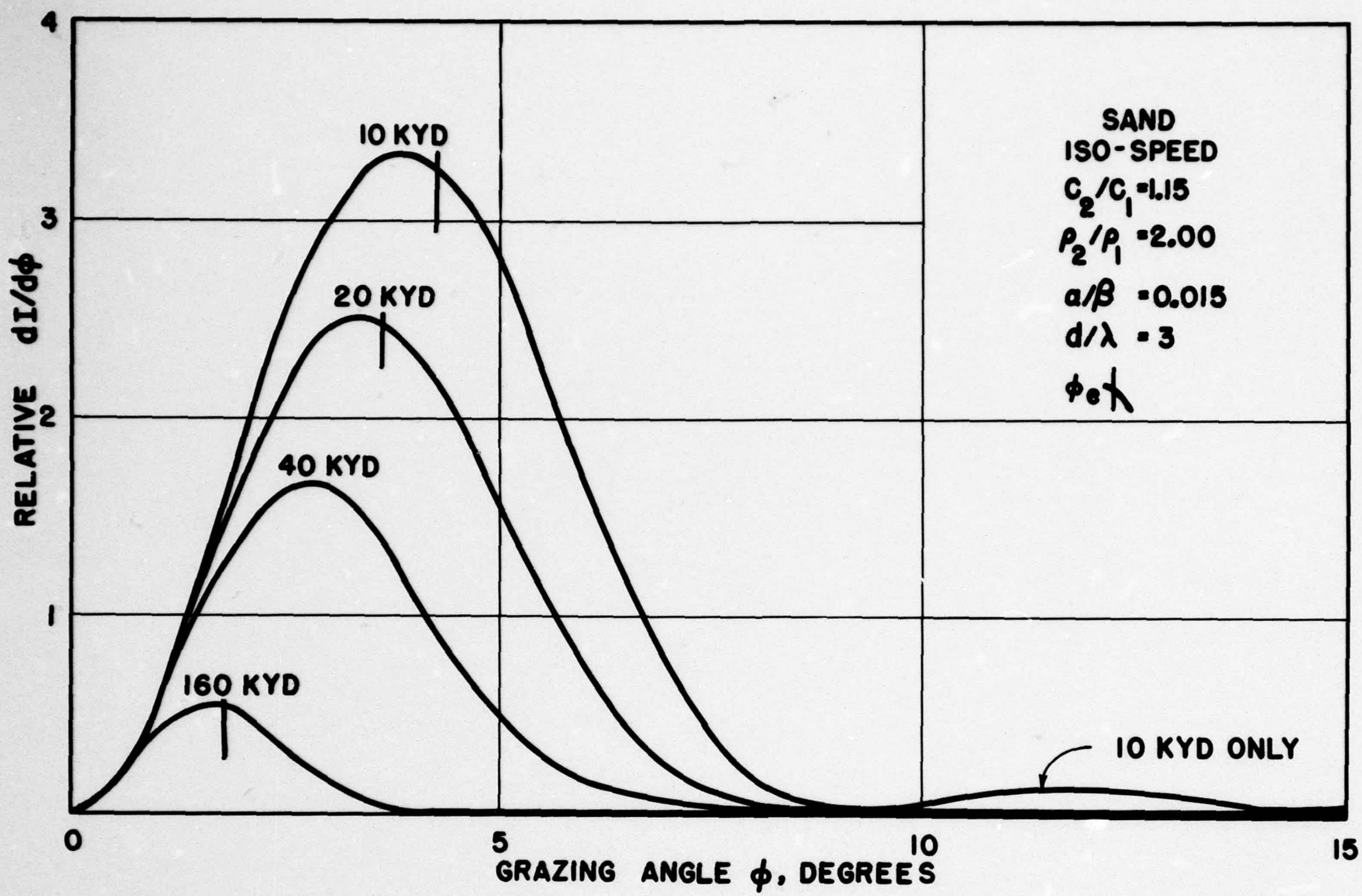

10 KYD
20 KYD
40 KYD
160 KYD
10 KYD ONLY
SAND
ISO-SPEED
$C_2/C_1 = 1.15$
$\rho_2/\rho_1 = 2.00$
$a/\beta = 0.015$
$d/\lambda = 3$
RELATIVE $dI/d\phi$
GRAZING ANGLE ϕ, DEGREES
0
5
10
15
1
2
3
4

FIG. 7

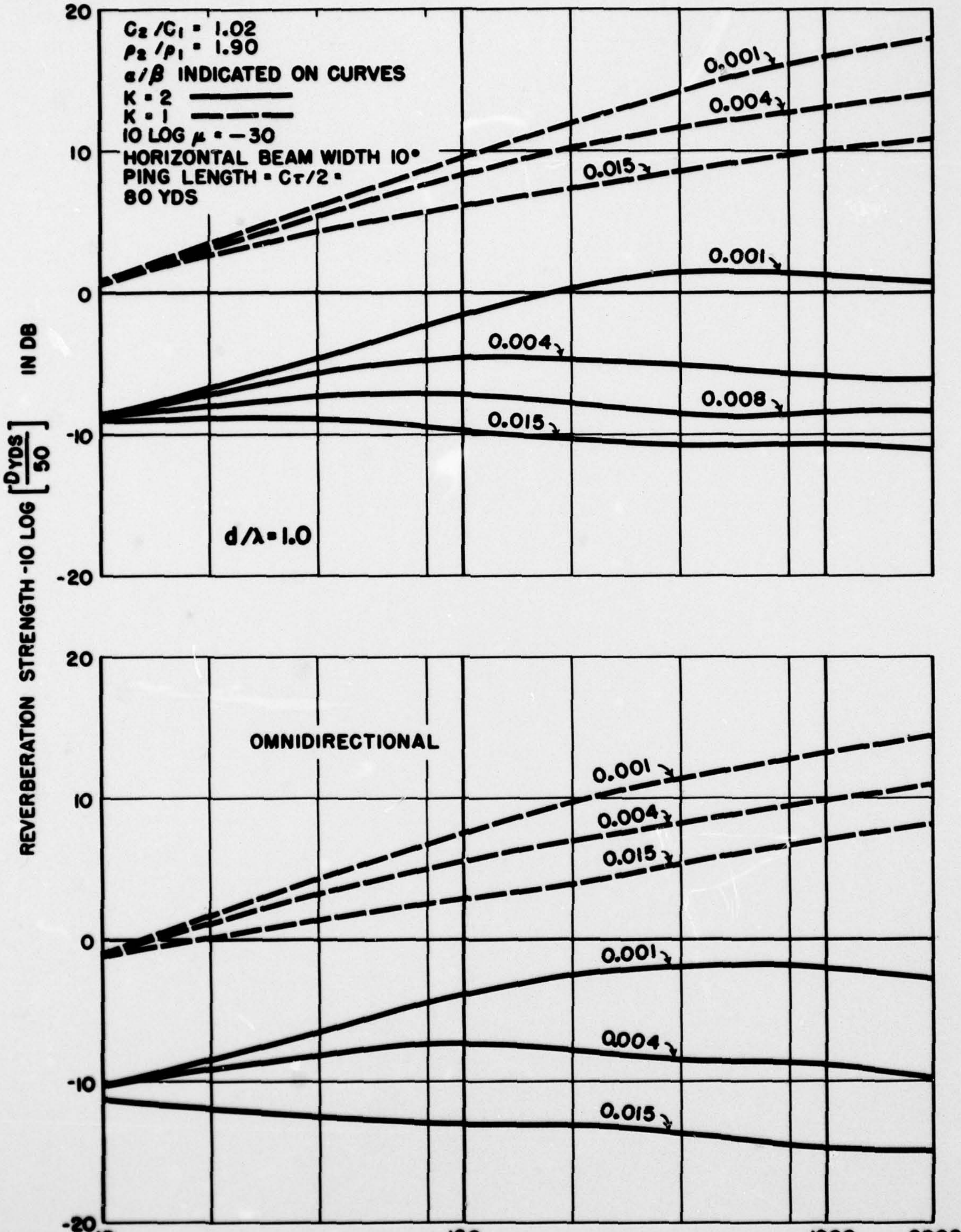
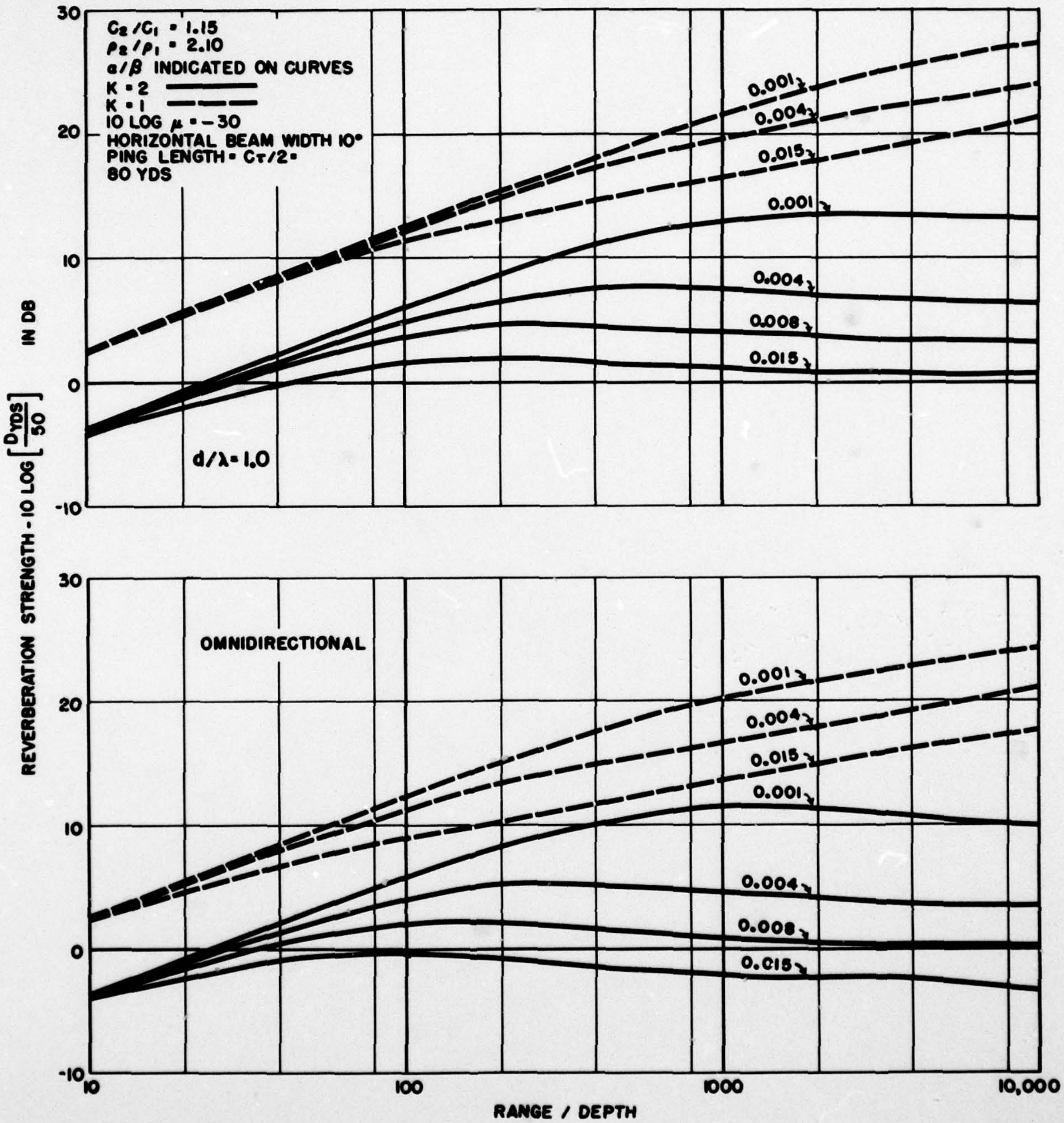
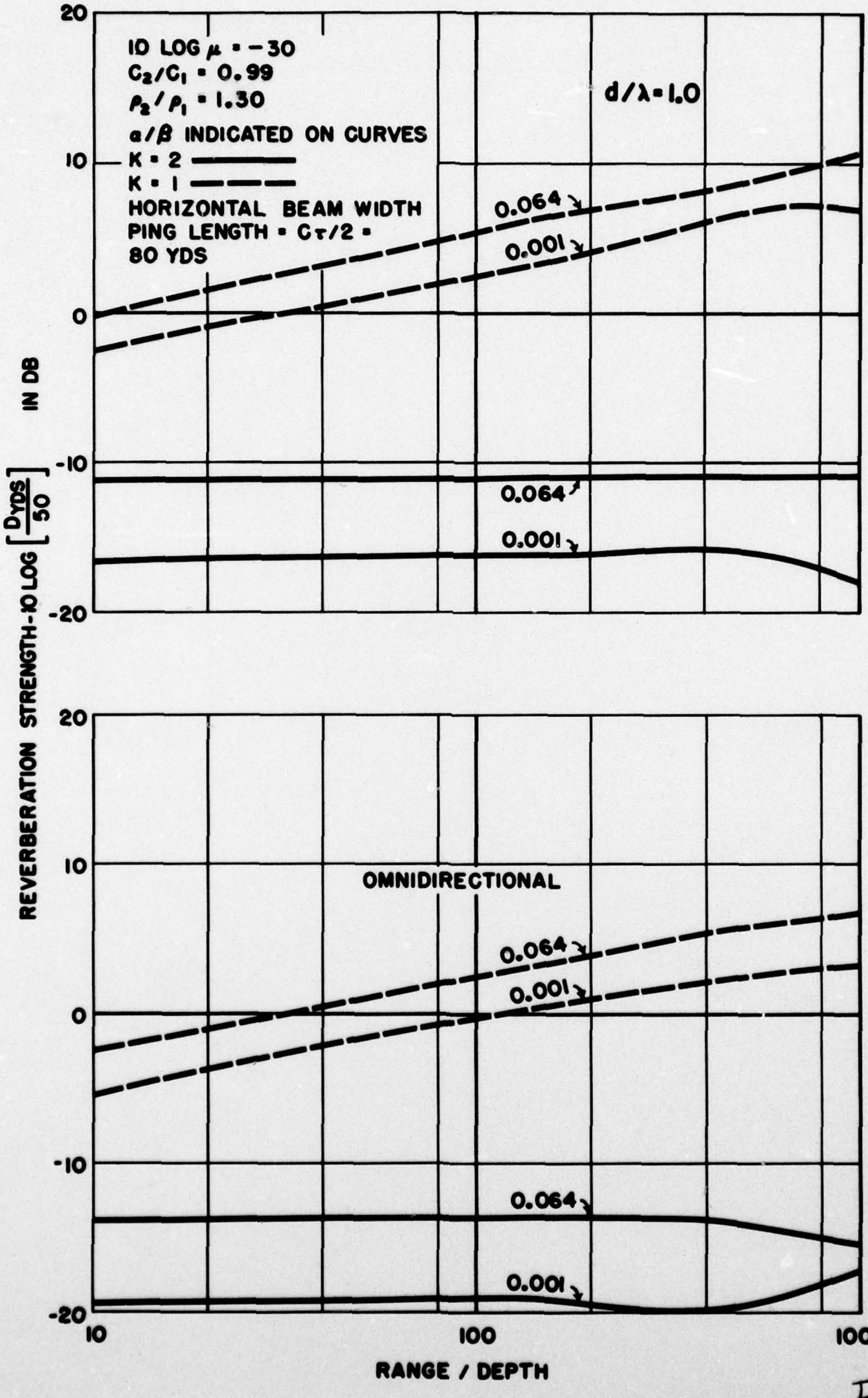

$C_2/C_1 = 1.02$
$\rho_2/\rho_1 = 1.90$
α/β INDICATED ON CURVES
K = 2
K = 1
10 LOG μ = −30
HORIZONTAL BEAM WIDTH 10°
PING LENGTH = $C\tau/2$ =
80 YDS
$d/\lambda = 1.0$
OMNIDIRECTIONAL
0.001
0.004
0.008
0.015
REVERBERATION STRENGTH −10 LOG $\left[\frac{D_{YDS}}{50}\right]$ IN DB
RANGE / DEPTH
20
10
0
-10
-20
100
1000
2000

FIG. 8



C2/C1 = 1.15
ρ2/ρ1 = 2.10
α/β INDICATED ON CURVES
K = 2
K = 1
10 LOG μ = -30
HORIZONTAL BEAM WIDTH 10°
PING LENGTH = Cτ/2 = 80 YDS
d/λ = 1.0
OMNIDIRECTIONAL
0.001
0.004
0.015
0.001
0.004
0.008
0.015
REVERBERATION STRENGTH - 10 LOG [D YDS / 50] IN DB
RANGE / DEPTH
10
100
1000
10,000
30
20
10
0
-10

FIG 9



10 LOG μ = −30
C2/C1 = 0.99
ρ2/ρ1 = 1.30
α/β INDICATED ON CURVES
K = 2
K = 1
HORIZONTAL BEAM WIDTH
PING LENGTH = Cτ/2 = 80 YDS
d/λ = 1.0
0.064
0.001
0.064
0.001
OMNIDIRECTIONAL
0.064
0.001
0.064
0.001
REVERBERATION STRENGTH - 10 LOG [DYDS/50] IN DB
20
10
0
-10
-20
20
10
0
-10
-20
10
100
1000
RANGE / DEPTH

FIG. 10

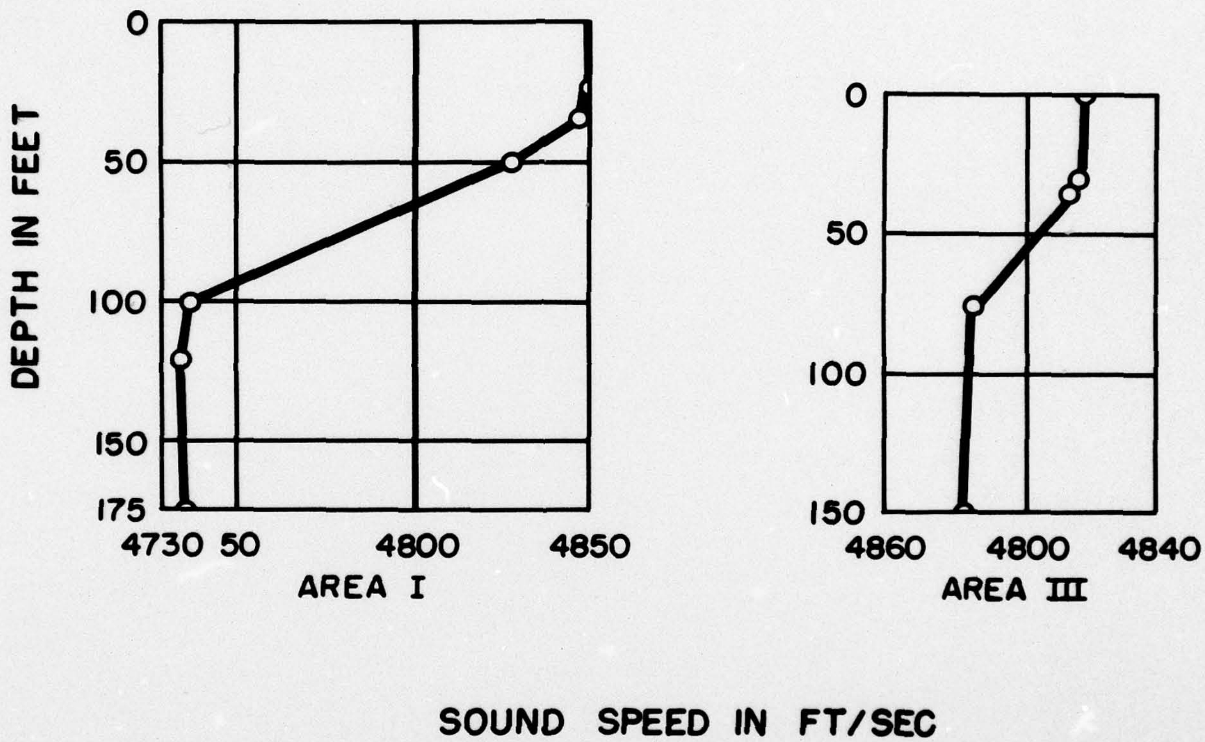
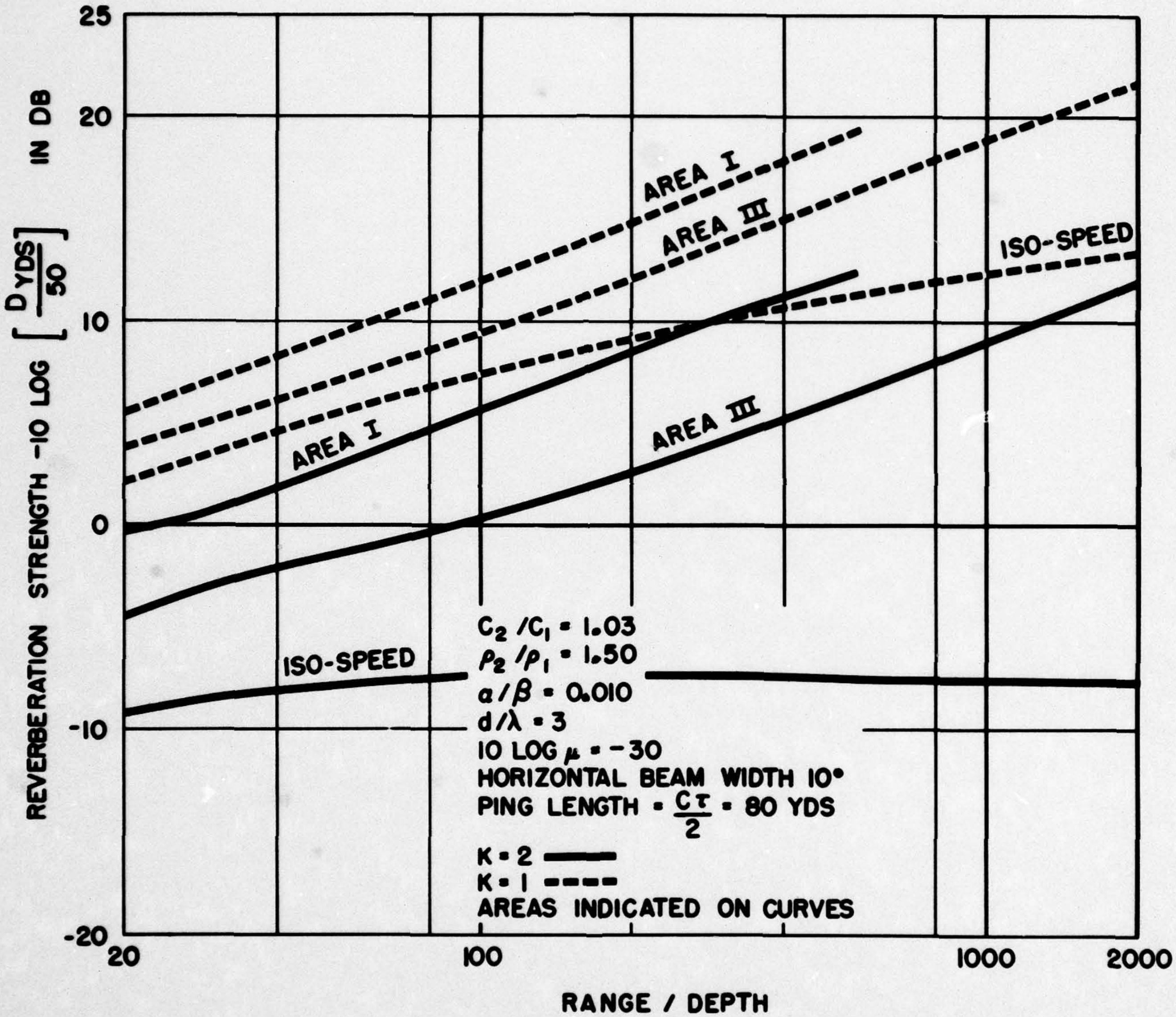

DEPTH IN FEET
0
50
100
150
175
4730 50
4800
4850
AREA I
0
50
100
150
4860
4800
4840
AREA III
SOUND SPEED IN FT/SEC

FIG. 11



REVERBERATION STRENGTH -10 LOG [D YDS / 50] IN DB
25
20
10
0
-10
-20
20
100
1000
2000
RANGE / DEPTH
AREA I
AREA III
ISO-SPEED
AREA I
AREA III
ISO-SPEED
C_2/C_1 = 1.03
ρ_2/ρ_1 = 1.50
a/β = 0.010
d/λ = 3
10 LOG μ = −30
HORIZONTAL BEAM WIDTH 10°
PING LENGTH = $\frac{C\tau}{2}$ = 80 YDS
K = 2
K = 1
AREAS INDICATED ON CURVES

FIG. 12